MOTOROLA INC.

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Inventor(s) will not fill in	
Operation CMD Research	
DISCLOSURE NO. 0146m	DATE DEC 03 1996
Patent Committee Action	
Inventor(s) Name(s)	

MOTOROLA PATENT COMMITTEE

DISCLOSURE FOR PATENT COMMITTEE

SUBMITTED PURSUANT TO EMPLOYMENT AGREEMENT

FOR INSTRUCTIONS FOR COMPLETION REFER TO DISCLOSURE INSTRUCTION PROCEDURE

Inventor must fill in items 1 thru 12.
Items 2 to 5 may require extra sheets. BE SURE they are signed, witnessed and attached.

1. **Name of the invention. (Limit to ten words.)**
   Timing and Frequency Synchronization Method For Multicarrier Communication Systems
2. **State the problem(s) resolved by the invention.**
   See attached.
3. **Describe the invention in detail. Include its operation, purpose, environment and how problem(s) were solved. (Use separate sheets as required).**
   See attached.
4. **What new elements (e.g. components, circuits, process steps) or combination of known elements or software algorithm produced the improvement(s) over known technology?**
   See attached.
5. **List the closest known technology (attach article, patent, catalog sheet or other documentation).**
   Convential timing and frequency synchronization methods for MCM systems. See attached.
6. **What are the potential applications for use of this invention?**
   See attached.
7. **Conception date?** 10-07-96 **(Attach earliest log sheets, drawings, etc., to support dates).**
8. **To whom did you first disclose this invention? Name:** Phillip Rasky **Date:** 10-10-96
9. **Date the device was first built and tested.** ______ Device has not been built
   Present location of the device?

DETERMINATION OF LEGAL INVENTORSHIP FOR PATENT APPLICATION MUST BE MADE BY THE PATENT DEPARTMENT.

Inventor's signature (IMPORTANT — YOU *MUST* USE YOUR FULL FIRST, MIDDLE AND LAST NAMES).

10. **Inventor's Full Name: (Type)**

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12. Inventor's Full Name: (Type) | Signature | Date | Social Security No.

Home Address: Street | City | State | Country | Zip Code

Citizen of (i.e. U.S., Germany, etc.) | Dept. No. | Phone | Room No. | Employee Status
☐ Permanent
☐ Contractor

Witness signatures (TWO WITNESSES ARE REQUIRED).
Witness must sign and date this form *and all attachments*.
THE WITNESSES IN SIGNING THIS FORM ATTEST TO THE FACT THAT THEY UNDERSTAND THE INVENTION.

13. Witness Name: (Type) Bruce Mueller Signature Bruce Mueller Date 10-24-96 Phone 576-1320

14. Witness Name: (Type) Brian Classon Signature Brian K Classon Date 10-24-96 Phone 576-5675

Items 15 to 25 are to be filled in by the ENGINEERING and MARKETING/PRODUCT MANAGER or equivalent. Use separate sheets as required.
THE MANAGERS IN SIGNING THIS FORM ATTEST THAT THEY UNDERSTAND THE INVENTION.

15. **What product will this invention be used in? (No code names — use brief description if necessary)**
Intended for use in the comm. system being developed under the Advanced Comm. Systems Research project.

16. **When (was) (will) the first offer for sale of a product incorporating this invention (be) made?**
Date: ____________ Not known

17. **When is the estimated shipping date?** Not known

18. **When (was) (will) the first disclosure outside of Motorola (be) made? How and to whom? Nondisclosure agreement signed? State title and date of publication, if any.**
No disclosure outside Motorola

19. **What is the market for products incorporating this invention? Be specific and quantitative.**
Multimedia communication systems such as those being proposed for internet access, wireless local loop, and satellite communications. Examples would be systems being designed for the ITU's FPLMTS/IMT2000.

20. **Who are the potential competitors? What is the possibility this invention will be used by competitors? Which ones?** AT&T, Lucent Technologies, Telia Research, Ericsson, Nokia, and any other company insterested in multimedia communication systems

21. **Did this invention result from work on a development Contract? (YES) (NO) Contract No.______________**
Who was the contracting party?
No

22. **Discuss the business impact that this invention will have on Motorola. Be specific and quantitative.**
Depending on which technologies are chosen for future multimedia communication systems, this invention could have a significant positive business impact on Motorola.

23. Engineering Managers Name (Type)	Signature	Date	Dept. No.	Phone
Phillip Rasky	Phillip J Rasky	10-24-96	AE598	576-4580

24. Product/Marketing Managers Name (Type)	Signature	Date	Dept. No.	Phone

25. **The Manager must determine the security classification of this information. See Personnel Policy #840, and Corporate SOP E60, Protection of Proprietary Information.**

2. STATE THE PROBLEM(S) RESOLVED BY THE INVENTION.

Synchronizing the transmitting and receiving hardware is a necessary step for achieving reliable communications in wireless radio systems. The synchronization process can be broken down into two main parts, frequency synchronization and timing synchronization. Frequency synchronization involves measuring and compensating for the difference in frequency between the transmitting hardware's oscillator and the receiving hardware's oscillator. Timing synchronization involves adjusting the receiver's decimation phase such that the ensuing demodulation process occurs at the prespecified baud boundaries. Improper frequency synchronization results in a frequency offset in the received signal, while improper timing synchronization results in intersymbol interference. In either case, improper synchronization yields unreliable communications.

For single carrier systems, achieving proper synchronization is a fairly straightforward problem and, as such, many solutions exist in the art. For multicarrier, or orthogonal frequency division multiplexed (OFDM), systems, achieving synchronization is more difficult. While frequency synchronization in OFDM systems is a well defined problem, timing synchronization is inherently ambiguous. The reason for this ambiguity is that most OFDM systems make use of a guard interval in order to combat intersymbol interference (ISI) due to channel multipath. As shown in Figure 1, this guard interval consists of a cyclic extension of an OFDM baud.

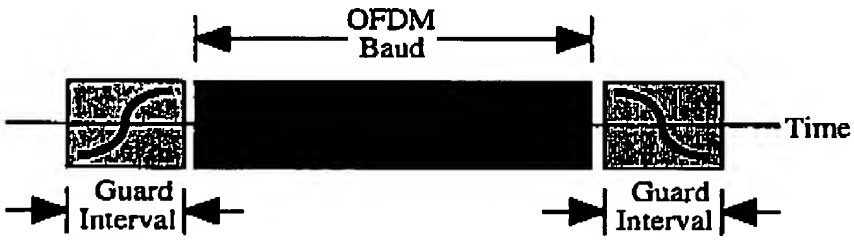

Figure 1. Representation Of The Guard Interval Used In OFDM Systems

The underlying premise is that the guard interval will absorb the multipath in the channel and provide for one or more ISI-free sampling points. The receiver can adjust its decimation phase, allowing any samples in the original baud corrupted by ISI to be "replaced" by samples in the guard interval during demodulation. Baud boundary ambiguity arises because of the possible presence of more than one ISI-free sampling point. Furthermore, adjusting the decimation phase to include samples from the guard interval leads to phase rotations between successive OFDM subcarriers after demodulation. More specifically, including n samples from the guard interval yields a $360 \cdot (n/L)$ degree phase shift between successive subcarriers, where L is the demodulator's FFT size. If ignored, this sampling phase induced subcarrier rotation can cause channel estimation

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problems. Consequently, synchronization in OFDM systems is a three part process. The first two parts, frequency synchronization and timing synchronization, are much like their single carrier system counterparts, although the aforementioned ambiguity possibility remains a caveat. The third part, rotation estimation, is unique to multicarrier systems and involves measuring the per-subcarrier rotation resulting from the chosen decimation phase.[1]

Methods for achieving synchronization in OFDM systems exist in the art, although most either ignore the rotation estimation stage, or are highly inefficient in that they require the transmission of many known training symbols. For example, an OFDM synchronization method developed by Timothy M. Schmidl and Donald C. Cox of Stanford University [1] is similar to the method presented here, but requires twice the number of training symbols and neglects to measure the per-subcarrier rotation. Ignoring the rotation can cause channel estimation problems, while having large numbers of training symbols reduces maximum data throughput and results in higher overhead and lower spectral efficiency. A better method for achieving synchronization in OFDM systems is needed. This method should require low overhead and low computational complexity and needs to include the per-subcarrier rotation measurement.

3. DESCRIBE THE INVENTION IN DETAIL. INCLUDE ITS OPERATION, PURPOSE, ENVIRONMENT, AND HOW PROBLEM(S) WERE SOLVED.

The present invention is based largely on the Schmidl/Cox synchronization algorithm [1] mentioned above. As with the Schmidl/Cox algorithm [1], the present invention provides a method for achieving timing and frequency synchronization between the transmitting and receiving hardware in OFDM-based radio communication systems. However, in contrast to the Schmidl/Cox algorithm [1], it also provides for per-subcarrier rotation estimation, and uses only half the number of training symbols.

The heart of the present invention is a single training baud located at the beginning of each transmitted signal frame. This training baud consists of a sequence of known symbols transmitted only on the even-numbered OFDM subcarriers. Null symbols are transmitted on the unused odd-numbered OFDM subcarriers. The power of the known symbols is doubled such that the overall transmit power remains unchanged. After the IFFT modulation process in the transmitter, the double power known symbols interlaced with the null symbols yield a baud waveform whose first and second halves are identical. The structure of the training baud is shown in Figure 2.

[1] Note that the per-subcarrier rotation problem can be ignored in multicarrier systems which are self-contained in frequency. These systems can be viewed as the superposition of multiple single carrier systems, in that all information necessary to demodulate a particular subcarrier (pilot symbols, reference symbols, etc.) lies on that subcarrier. Because no cross-subcarrier interpolation is performed, the per-subcarrier rotation does not cause any problems.

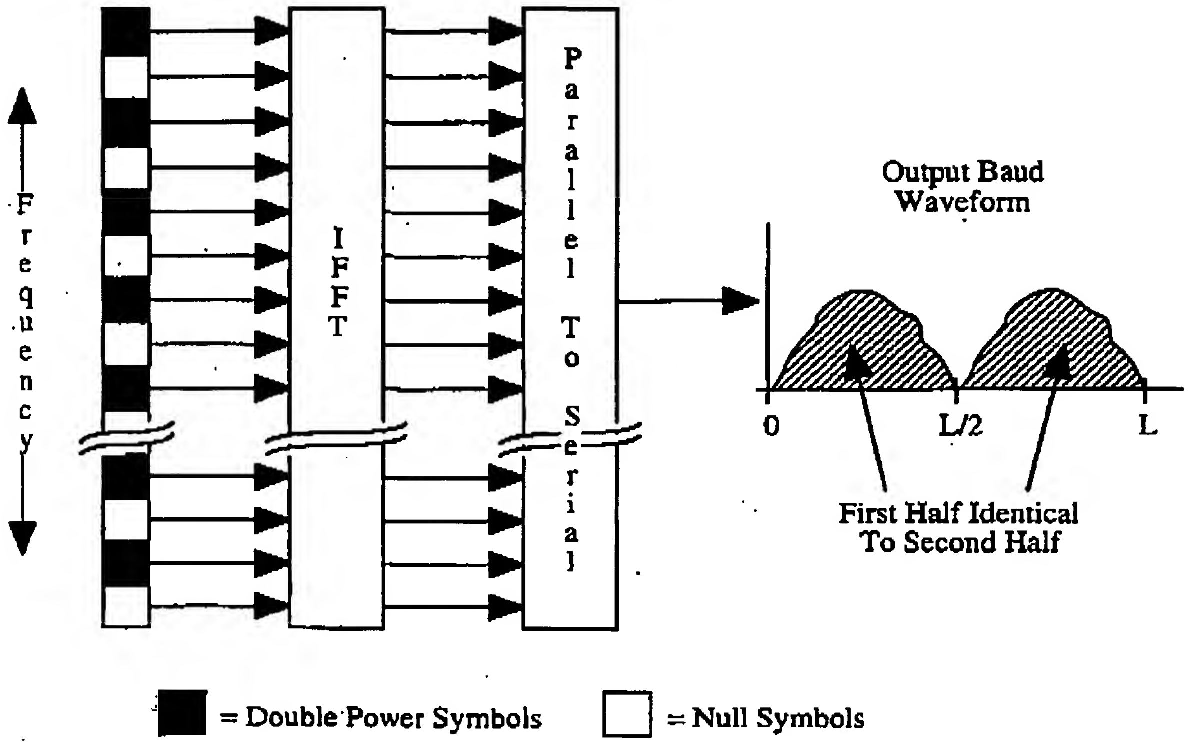

Figure 2. Structure Of Training Baud For OFDM Synchronization Method

This training baud is identical in format to the first of the two training bauds used by the Schmidl/Cox algorithm [1]. The present invention can be used both in an acquisition state and a tracking state. In the acquisition state, the receiver searches for an OFDM baud whose first and second halves are identical. This initial searching process occurs in the "time domain", before the FFT demodulator. Assuming that the symbol duration is L, this search can be accomplished using the following correlation metric:

$$P(d)=\frac{\sum_{m=0}^{\frac{L}{2}-1} r^*(d+m)r(d+m+\frac{L}{2})}{\sqrt{\sum_{m=0}^{\frac{L}{2}-1} r^*(d+m)r(d+m)}\cdot\sqrt{\sum_{m=0}^{\frac{L}{2}-1} r^*(d+m+\frac{L}{2})r(d+m+\frac{L}{2})}}$$

where the r's are the received samples, after the A/D and before the FFT, and d is the time index. Searching in this manner is very similar to performing differential demodulation on samples spaced by $L/2$ and integrating the differential demodulator output over a length $L/2$ rectangular window. In examining this output, the proper decimation phase occurs at the point where the magnitude of the correlation metric is maximized:

$$d_{opt} = \underset{d}{\arg\max} |P(d)|$$

Because the search process includes the OFDM guard interval, the valid region of the correlation function will look more like a "plateau" than a single spike. The presence of channel multipath will not affect the first half/second half symmetry of the training baud, but it will result in a narrower correlation plateau. Since the effects of the channel phase cancel when correlating the two halves of the baud, at the proper decimation phase the only phase shift between the first and second halves of the baud should result from a frequency offset. Because of the nature of fixed frequency offsets, samples separated by a constant time period will have a constant phase shift between them. Taking the magnitude of the metric eliminates the effect of frequency offset on timing synchronization.

Once timing synchronization has been established, one can use the angle of the metric computed at the proper decimation phase to obtain an initial estimate of the frequency offset, as shown below:

$$\gamma_1 = \angle P(d_{opt}) \cdot \frac{\Delta f}{\pi}$$

where Δf is the subcarrier spacing in Hz. As mentioned earlier, the correlation metric, $P(d)$, can be viewed as the integral of a differential demodulator's output. Therefore, the phase of the correlation metric is equal to the signal's average rotation over a length $L/2$ time interval, which, in turn, is directly related to the underlying frequency offset. Unfortunately, because of the inherent aliasing in computing angles, γ_1 only gives a measure of the offset to the nearest even numbered subcarrier. In other words, correcting a received signal by $-\gamma_1$ Hz will ensure that the frequency offset remaining in the signal is a multiple of twice the subcarrier spacing. The portions of the present invention described above are identical to their counterparts from the Schmidl/Cox algorithm [1]. The novel portions of the present invention are described in the following sections. Assuming that this initial frequency correction is performed, one can then demodulate the training baud using the receiver's FFT and measure the remaining frequency offset. Measuring and correcting the remaining frequency offset requires knowing the value of the symbols transmitted on the even subcarriers within the training baud. A differential correlation can then be performed between the known symbols and various subcarrier-shifted versions of the demodulated symbols. The subcarrier shift resulting in the largest differential correlation will give a measure of the remaining frequency offset. Figure 3 gives an outline of this differential correlation process.

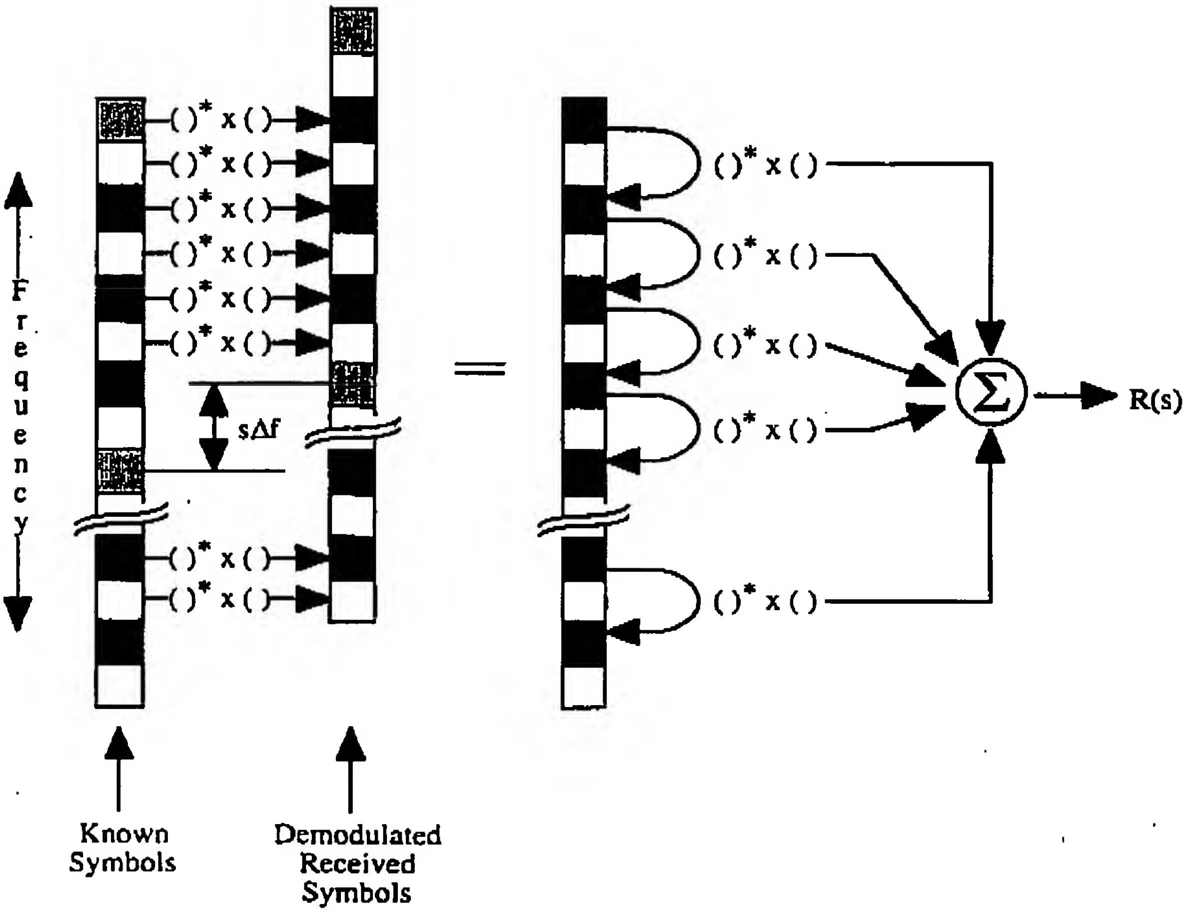

Figure 3. Differential Correlation Process For Measuring Remaining Frequency Offset

Assuming that the complex symbols output by the demodulator's FFT are given by $y(k)$ and that the known symbols modulated onto the even subcarriers are given by $x(k)$, then the differential correlation metric can be represented as follows:

$$R(s) = \sum_{k=0}^{L-1} \left[x^*(k) y((k+s) \bmod L)\right]^* \cdot \left[x^*(k+2) y((k+2+s) \bmod L)\right]$$

where L is the FFT size, s is instantaneous subcarrier shift being considered, and k is the subcarrier index. The remaining frequency offset can be computed using the following formula:

$$\gamma_2 = \Delta f \cdot s_{rem} \quad \text{where} \quad s_{rem} = \underset{s}{\arg\max} \left|R(s)\right|$$

Note that the effects of the channel phase cancel when correlating differentially in frequency. Therefore, at the appropriate subcarrier offset, s_{rem}, any phase shift

remaining in the differential correlation metric can be attributed to sampling phase induced subcarrier rotation. Taking the magnitude of the differential correlation metric isolates the frequency synchronization process from the effects of subcarrier rotation. The Schmidl/Cox algorithm [1] uses a second training baud to measure this secondary frequency offset. A correlation is performed between the first training baud and subcarrier-shifted versions of the second baud in order to calculate the subcarrier frequency offset. The present invention uses only one training baud to accomplish the same task, and hence is more overhead efficient.

Once frequency synchronization has been established, one can use the angle of the differential correlation metric evaluated at the appropriate subcarrier offset to obtain an initial estimate of twice the per-subcarrier rotation, as shown below:

$$2\phi = \angle R(s_{rem})$$

This estimation process is inherent only to the present invention, as the Schmidl/Cox algorithm ignores subcarrier rotation entirely. Because of the inherent aliasing in computing angles, one cannot simply divide the above estimate in half in order to compute the true per-subcarrier rotation. As shown below, the above equation has two possible solutions, one positive and one negative:

$$\phi_+ = \max\left(\frac{\angle R(s_{rem})}{2}, \left[\frac{\angle R(s_{rem})}{2} + 2\pi\right] \mathrm{mod}\, 2\pi - \pi\right)$$

$$\phi_- = \min\left(\frac{\angle R(s_{rem})}{2}, \left[\frac{\angle R(s_{rem})}{2} + 2\pi\right] \mathrm{mod}\, 2\pi - \pi\right)$$

The following figure depicts the two solutions graphically:

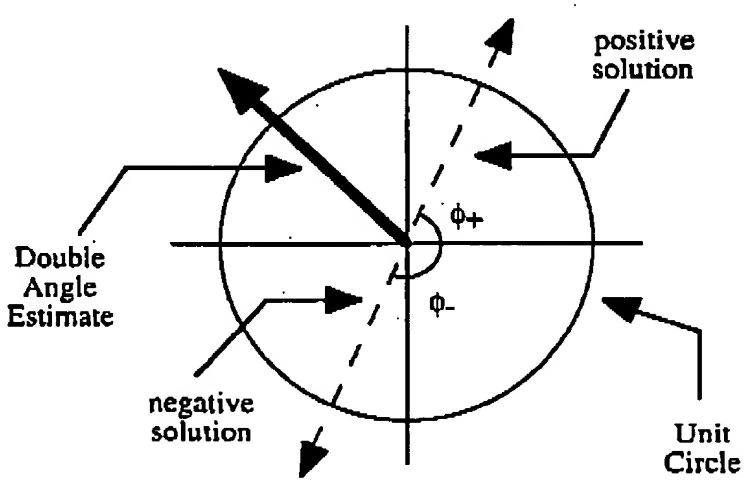

Figure 4. Two Solutions For Per-Subcarrier Rotation Estimate

The positive solution assumes that the chosen decimation phase occurs $\phi_+ \frac{L}{2\pi}$ samples after the beginning of the non-extended portion of the OFDM baud, while the negative solution assumes that the chosen decimation phase occurs $\phi_- \frac{L}{2\pi}$ samples before the beginning of the non-extended portion of the OFDM baud. In order to determine which solution yields the true per-subcarrier rotation, one can use the original half-symbol timing correlation function, $P(d)$, to check for the beginning of the non-extended portion of the OFDM baud. Note that the values comprising $P(d)$ do not need to be recalculated since they were computed earlier as part of the initial timing synchronization process.

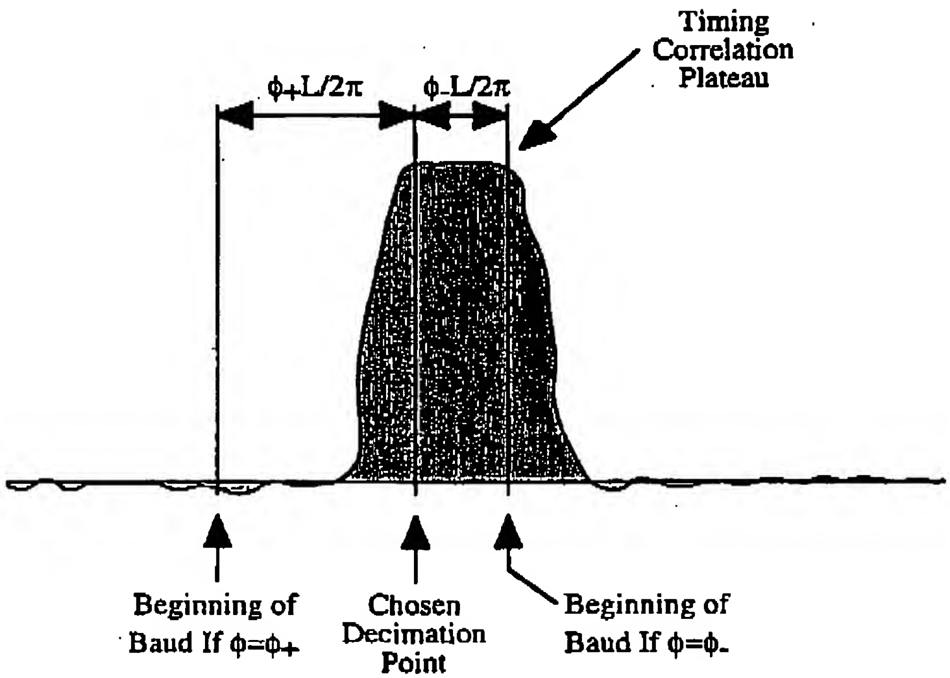

Figure 5. Using Timing Correlation Function To Find Per-Subcarrier Rotation

If the overall length of the guard interval is less than half the baud length (which is generally the case), then only one of the "baud beginnings" will lie on the timing correlation plateau. The other baud beginning will lie within the noise floor. Using this technique, the final choice for the per-subcarrier rotation phase becomes:

$$\phi = \begin{cases} \phi_+ & \text{if } \left| P\left(d_{opt} - \phi_+ \frac{L}{2\pi}\right)\right| > \left| P\left(d_{opt} - \phi_- \frac{L}{2\pi}\right)\right| \\ \phi_- & \text{if } \left| P\left(d_{opt} - \phi_- \frac{L}{2\pi}\right)\right| < \left| P\left(d_{opt} - \phi_+ \frac{L}{2\pi}\right)\right| \end{cases}$$

The performance of the synchronization method in tracking mode is similar to that in acquisition mode, except that the number of computations is reduced. Timing correlations which search for a baud with identical first and second halves need only be performed over a small region near the current decimation phase. Moreover, assuming minimal oscillator drift and a fairly constant channel, only the initial frequency correction involving the angle of the timing correlation metric need be performed, and the more computationally intensive post-FFT-correlation can be avoided. Finally, if the post-FFT-correlation is in fact needed, a subset of the subcarriers can be used to compute the secondary frequency offset and the per-subcarrier rotation phase.

As a final note, Figure 6 summarizes the steps comprising the present invention.

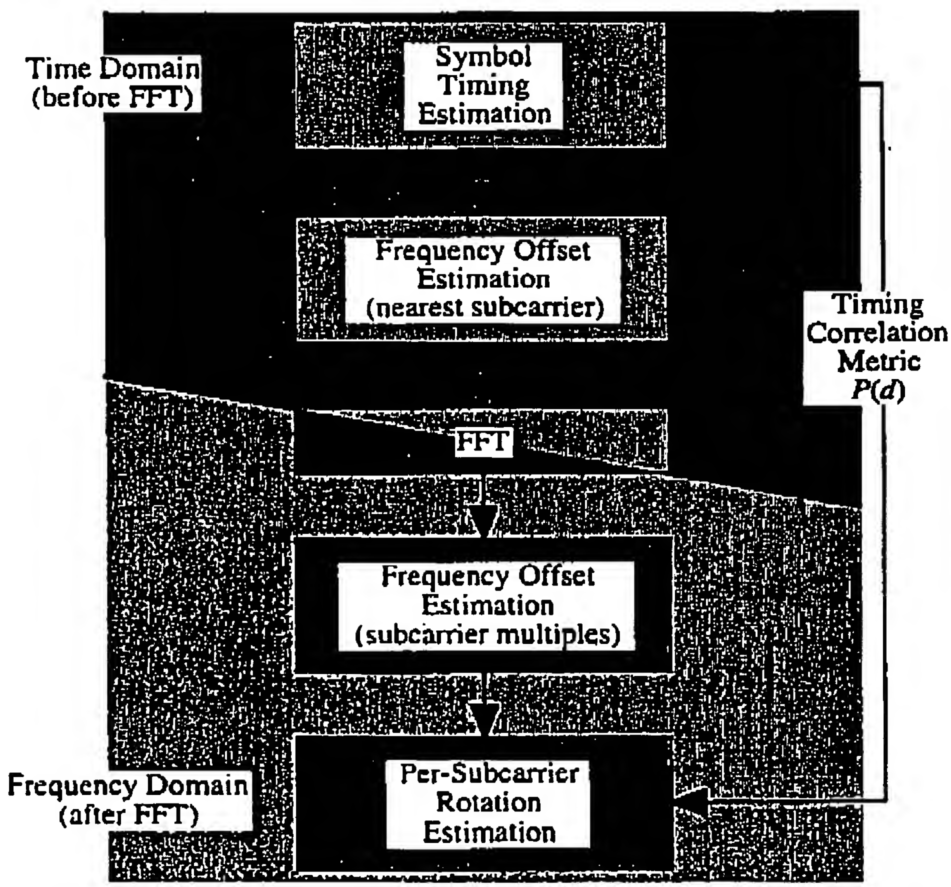

Figure 6. Summary Of The Steps Comprising The Present Invention

4. WHAT NEW ELEMENTS (E.G. COMPONENTS, CIRCUITS, PROCESS STEPS) OR COMBINATION OF KNOWN ELEMENTS OR SOFTWARE ALGORITHMS PRODUCED THE IMPROVEMENT(S) OVER KNOWN TECHNOLOGY?

The OFDM synchronization method detailed in the last section possesses the following advantages:

1. The method is very overhead efficient. Unlike prior art synchronization methods which require upwards of two OFDM training bauds, the present invention needs at most one OFDM training baud. Moreover, by replacing some of the known symbols in the training baud with random data symbols, this overhead can be further reduced. The initial half-symbol timing correlation process looks for a baud whose first and second halves are identical. This property depends only on the fact that every other subcarrier contains information. Whether this information consists of known symbols or random data symbols has no impact on this process. However, reducing the number of known symbols implies that the post-FFT correlation used to measure subcarrier shift and per-subcarrier rotation operates over a shorter sample size. In noisy environments, shorter correlations tend to be less reliable than longer ones.
2. The method accomplishes all three stages of synchronization. Most prior art OFDM synchronization methods ignore the per-subcarrier rotation. This method, not only performs timing and frequency synchronization, but also measures the ensuing per-subcarrier rotation phase.

5. LIST THE CLOSEST KNOWN TECHNOLOGY (ATTACH ARTICLE, PATENT, CATALOG SHEET OR OTHER DOCUMENTATION)

The present invention is intended to be an improvement on prior art multicarrier timing and frequency synchronization methods.

<u>REFERENCES</u>

[1] T.M. Schmidl and D.C. Cox, "Low-Overhead, Low-Complexity [Burst] Synchronization for OFDM," *Proceedings of ICC 1996*, vol. 3, pp 1301-1306.

6. WHAT ARE THE POTENTIAL APPLICATIONS FOR USE OF THIS INVENTION?

Any communication system using orthogonal frequency division multiplexing (OFDM) technology can benefit from this invention. OFDM is currently in use in Europe for Digital Audio Broadcasting (DAB) and Digital TV (DTV) applications and is being considered for Asymmetric Digital Subscriber Line (ADSL) services in the United States. Furthermore, OFDM is also being considered for several future high data rate wireless systems worldwide.